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Optical Mixing with Difference Frequencies to 552 GHz in Ultrafast High Electron Mobility Transistors

M. E. Ali, K. S. Ramesh, H. R. Fetterman, *Fellow, IEEE*, M. Matloubian, *Member, IEEE*, and G. Boll

Abstract—The technology of optical mixing in three-terminal devices has been extended, for the first time, to submillimeter-wave frequencies. Using a new generation of 50-nm gate InP-based high electron mobility transistors (HEMT's), optically mixed signals were detected to 552 GHz with a signal-to-noise ratio of approximately 5 dB. A novel harmonic three-wave mixing scheme was used for the detection of the optically generated signals. The technique involved downconversion of the signal in the device by the second harmonic of a gate-injected millimeter-wave local oscillator.Measurements were also done at 212 and 382 GHz to estimate the absolute signal strength and conversion losses. Finally, new interesting features in the bias dependence of the optically mixed signal are reported.

Index Terms—High electron mobility transistors (HEMT's), millimeter-wave generation, optical heterodyning, optical mixing, photodetectors, phototransistors, terahertz frequencies.

I. Introduction

FIBER-OPTIC links and a variety of photonic schemes have been incorporated to increasingly larger extent in current generations of microwave and millimeter-wave systems due to numerous advantages that come from operating in the optical domain [1], [2]. Consequently, there has been a growing demand for large photoresponse bandwidth on electronic devices that constitute critical functional elements of such systems. Of all the devices that can provide the required bandwidth, high electron mobility transistors (HEMT's) stand out to be particularly important as they form a unique class of three-terminal devices that exhibit excellent low-noise millimeter-wave characteristics. The presence of the third terminal, in contrast to two-terminal devices, plays a significant role in realizing multifunctionality and enhancing the performance of the devices. In this letter, we explore the high-frequency capabilities of a new generation of 50-nm gate pseudomorphic HEMT's in continuous-wave optical mixing experiments. In our earlier work, we have performed optical mixing in these devices beyond 200 GHz using a three-wave detection configuration [9]. In our effort to test these devices at even higher frequencies, we employed a harmonic three-wave detection scheme. Using this scheme and an improved detection circuitry, we extended our results to 552 GHz, which sets a new record of the highest frequency optical mixing in three-terminal devices to date. The measurement involved downconversion of the 552-GHz signal in the device by the second harmonic of a local oscillator injected at the gate. A signal-to-noise ratio of approximately 5 dB was obtained. Measurements at 212 and 382 GHz were also performed to estimate the conversion losses of our detection schemes. In our last measurement, we investigated the bias dependence of the optically mixed signal and made new observations that indicated participation of both the barrier and channel/buffer layers of the HEMT in the optical mixing process.

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II. Device Characteristics

The HEMT's used in our experiments were fabricated using an InP-based AlInAs–GaInAs material system. Significant improvement in the electrical performance was achieved due to the growth of pseudomorphic GaInAs channel with 80% In and the reduction of gate lengths to 50 nm in a self-aligned fabrication process [4]. *S*-parameter measurements conducted on a vector network analyzer to 110 GHz yielded extrapolated cutoff frequencies of 228 GHz and maximum oscillation frequencies of 124 GHz for these devices. Optical response characteristics were obtained from dc photocurrent and picosecond electrooptic sampling measurements at visible red wavelengths. The devices exhibited responsivity of 74 A/W and a response time of approximately 6.9 ps [3].

III. Optical Mixing at Submillimeter-Wave Frequencies

The experimental arrangement for optical mixing is shown in Fig. 1. The beating dye and HeNe beams were combined by a beam splitter and focused on the device under test using an objective lens. The dye wavelength was continuously monitored on a wavemeter. The devices were contacted and biased with coplanar probes and bias tees. The probes (Picoprobe, model 220-GSG- 100-BT), designed to operate in the *G*-band, served to guide and couple millimeter-wave signals to on-wafer devices. The optically generated millimeter waves were first downconverted and then launched into an external waveguide via the probe on the drain side. This removes the constraints imposed by the RF contact probes for the detection of signals whose frequencies lie beyond their bandwidth. The signals were then detected in a millimeter-wave receiver. The receiver consisted of a subharmonically pumped mixer, a 105-GHz InP Gunn diode as local oscillator, and low-noise IF amplifiers. The receiver covered an IF band of 1–5 GHz centered around 210 GHz and had a nominal conversion gain of 49 dB with a noise figure of approximately 9.2 dB.

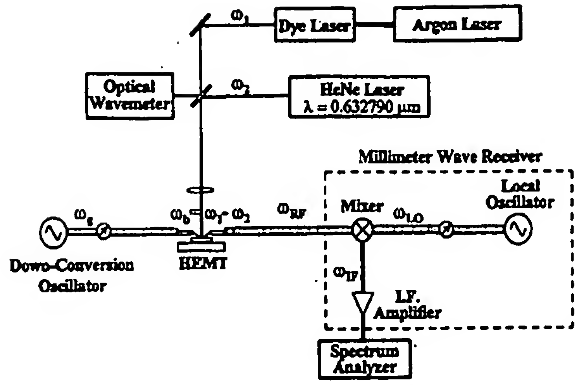

Fig. 1. Optical mixing arrangement in the three-wave detection configuration. The optically generated signals are downconverted in the HEMT's by injection of a millimeter-wave local oscillator signal to keep the resultant in the bandwidth of the external millimeter-wave receiver.

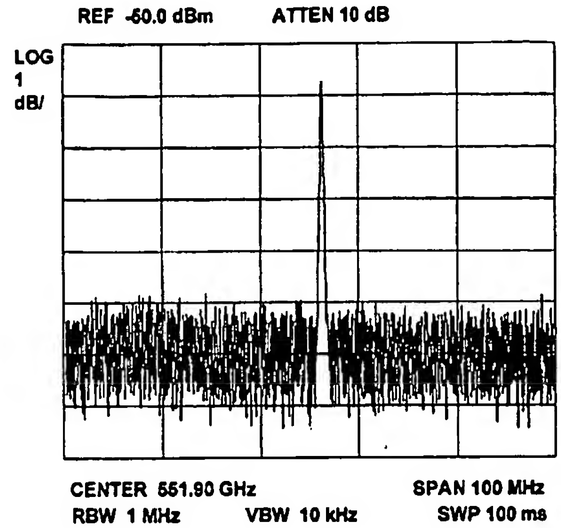

Fig. 2. Spectrum analyzer trace of the 552-GHz optically generated signal, downconverted in the HEMT's by the second harmonic of a gate-injected 170-GHz local oscillator to 212 GHz and detected in the external millimeter-wave receiver.

Our present extension of optical mixing to submillimeter-wave difference frequencies in on-wafer HEMT devices makes use of a harmonic three-wave detection scheme. In this scheme, a millimeter-wave local oscillator is applied electrically to the gate terminal, which interacts with the optically mixed currents in the device. Higher order harmonics of the local oscillator are produced in the device due to its inherent nonlinearity. The beating of the optically mixed signal with each of the harmonics gives rise to different mixing products in the device. There are mixing products at $nf_{LO} \pm f_{OPT}$, where f_{LO} is the frequency of the local oscillator, n is the order of the harmonic, and f_{OPT} is the frequency of the optically generated RF signal. By proper choice of the local-oscillator frequency or the harmonic number, any optically generated signal can be downconverted to a frequency that falls into the detection bandwidth of the external receiver. Three-wave detection that involves downconversion of optically mixed signal with the fundamental local-oscillator frequency was successfully employed in our earlier work [3]. Due to the lack of easily available local-oscillator sources and difficulty in coupling to the device, the fundamental three-wave detection scheme cannot be extended to very high frequencies. Harmonic mixing overcomes these limitations due to its less stringent requirements on the local-oscillator frequency and coupling. Although similar harmonic techniques have been used in both optical heterodyne and microwave experiments [5], [6], what distinguishes our implementation from others is the downconversion of an extremely high optical beat frequency to a millimeter-wave intermediate frequency.

Using the above technique, we extended optical mixing to a record high frequency of 552 GHz in our ultrafast HEMT's. A 170-GHz Klystron was used as the local oscillator at the gate, the second harmonic of which downconverted the 552 GHz optically generated signal to an IF signal at 212 GHz. The IF signal was then launched into a waveguide and detected in the external millimeter-wave receiver. The spectrum analyzer trace of the signal is shown in Fig. 2. A signal-to-noise ratio of approximately 5 dB and a linewidth on the order of 1 MHz was obtained. For this measurement, the optical powers of the dye and HeNe lasers incident on the device were kept roughly at 1 mW each. The local-oscillator power at the gate was approximately 3 dBm. The device was optimally biased at a drain–source voltage of 0.6 V and a gate–source voltage of −0.4 V. At this bias, our HEMT's operate close to pinchoff, exhibiting strong nonlinearity and the three-wave detection process becomes very efficient. However, the strength of the optically mixed signals suffers due to reduced channel conductance of the device under such extreme operating conditions. Our results demonstrate the high-frequency capabilities of these HEMT devices although the signal is not very strong. The low signal power can be ascribed to a small optical absorption volume, which can be improved by employing a traveling-wave configuration and a poor coupling efficiency, which can be alleviated by using waveguide-fed structures.

One can estimate the efficiencies for both the fundamental and second-harmonic downconversion processes involved in our three-wave detection technique, given that the absolute power levels of the optically mixed signals in the device are known. To do this, we made direct measurements of an optically mixed signal at 212 GHz, where we have a good idea of the conversion and coupling loss/gain. We also assume that the device optical response rolls off at 20 dB/decade. The insertion loss of the RF output probe is 3 dB over the experimental range of interest. The additional loss in the coupling waveguide section and the microwave cable taking the signal to the spectrum analyzer is approximately 1 dB. The conversion gain of the external millimeter-wave receiver is 49 dB over the desired IF bandwidth. Therefore, the net conversion gain the signal experiences in going from the drain of the device to the spectrum analyzer is 45 dB. A −34.7-dBm spectrum analyzer signal strength at 212 GHz gives an absolute signal strength of −79.7 dBm for the optically generated signal in the device. Assuming a 20-dB/decade rolloff, we would expect the absolute strength to be −84.8 dBm for the optically generated signal at 382 GHz. The experimental value from three-wave

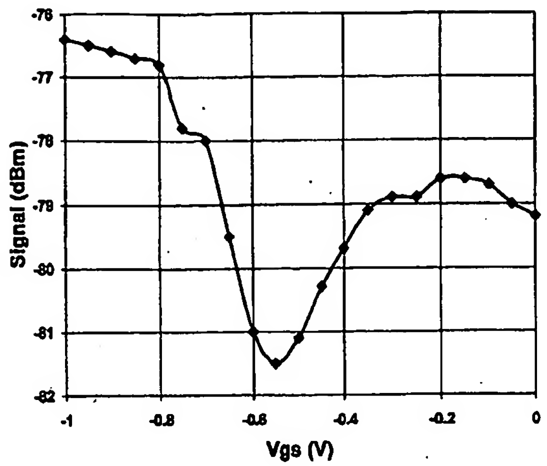

Fig. 3. Gate bias dependence of the optically mixed signal power at 212 GHz at a drain-to-source voltage of 0.6 V. This characteristic shape is attributed to photogeneration of carriers both in the barrier and channel/buffer regions.

detection is −87.7 dBm, giving a conversion loss of about 2.9 dB for the fundamental downconversion process. For the 552-GHz signal, based on the same approach, we would expect a power level of −88.0 dBm compared to the experimentally observed value of −95.7 dBm. This gives us a conversion loss of 7.7 dB for the second-harmonic downconversion process. The extra loss introduced in going from the fundamental to the second-harmonic downconversion process is 4.8 dB. The basic theory on harmonic mixing gives a 3-dB conversion loss for each higher order harmonic mixing term starting from the fundamental under ideal conditions [7]. The discrepancy can be attributed to the mismatch between the device and the external circuit.

An experimental study of the bias dependence of the optically generated signals led to interesting findings about optical processes taking place in our HEMT's at high frequencies. In this study, we measured the strength of the optically generated signal at 212 GHz as a function of the gate to source voltage, as plotted in Fig. 3. In contrast to typical monotonous decay of the signal strength with decreasing gate bias [8], [9], our observations show an initial decrease followed by an increase and eventual saturation of the signal power level. Measurements at other frequencies exhibited similar bias dependence eliminating any possibility of resonance effects. However, the minimum in Fig. 3 tends to shift toward more positive gate biases with increasing frequency. The trend can be explained by considering the photogeneration of carriers both in the barrier and in the channel/buffer layers of the device at visible wavelengths. A model, based on the transfer of photogenerated carriers from the barrier to the channel, has been developed to account for the observed bias dependence of the optically mixed signal [10].

IV. Conclusion

We have examined optical mixing in state-of-the-art InP-based pseudomorphic HEMT's up to submillimeter-wave frequencies. The excellent electrical and optical response characteristics of these devices allowed us to carry out optical mixing up to a record high frequency of 552 GHz. The signal was detected using a harmonic three-wave mixing technique where the second harmonic of the gate-injected local oscillator was used to downconvert the optically mixed signal in the device. The same setup also permitted fundamental mixing with the local oscillator to an optical difference frequency of 382 GHz. The conversion losses for the fundamental and second-harmonic three-wave detection schemes were estimated to be 2.9 and 7.7 dB, respectively. An investigation of the gate bias dependence of the optically generated signals revealed some new characteristic features. Our current efforts in this area include extension of optical mixing to higher frequencies, measurements at 1.3- and 1.55-μm wavelengths, consideration of design issues to improve device performance, and development of a suitable scheme for optoelectronic integration.

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